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H01Q 9/04

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H1Q QDX

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(54) Abstract Title
**Steerable-beam multiple-feed dielectric resonator antenna**

(57) A dielectric resonator antenna uses a plurality of feeds to produce several beams each having a 'boresight' (that is, a direction of maximum radiation on transmit, or a direction of maximum sensitivity on receive) in a different direction. Several such beams may be excited simultaneously to form a new beam in any arbitrary direction. The new beam may be incrementally or continuously steerable and may be steered through a complete 360 degree circle. The invention may be combined with an internal or external monopole antenna so as to cancel out the antenna backlobe or otherwise resolve the front/back ambiguity that rises with this type of dielectric resonance antenna.

When receiving radio signals, electronic processing of such multiple beams may be used to find the direction of those signals thus forming the basis of a radio direction finding device. Further, by forming a transmitting beam or resolving a receiving beam in the direction of the incoming radio signal, a 'smart' or 'intelligent' antenna may be constructed. The excitation of several beams together can, in some combinations, produce a system with a significantly greater bandwidth than a beam formed by exciting a single probe or aperture.

The antenna is non-cylindrical, e.g. a cone, frustrum, pyramid, hemisphere, torus, polygonal or oval prism, sphere, stepped cylinder or less regular shape.

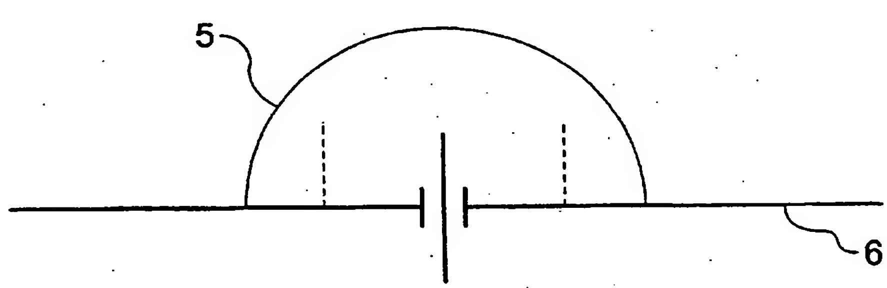


Fig. 9a

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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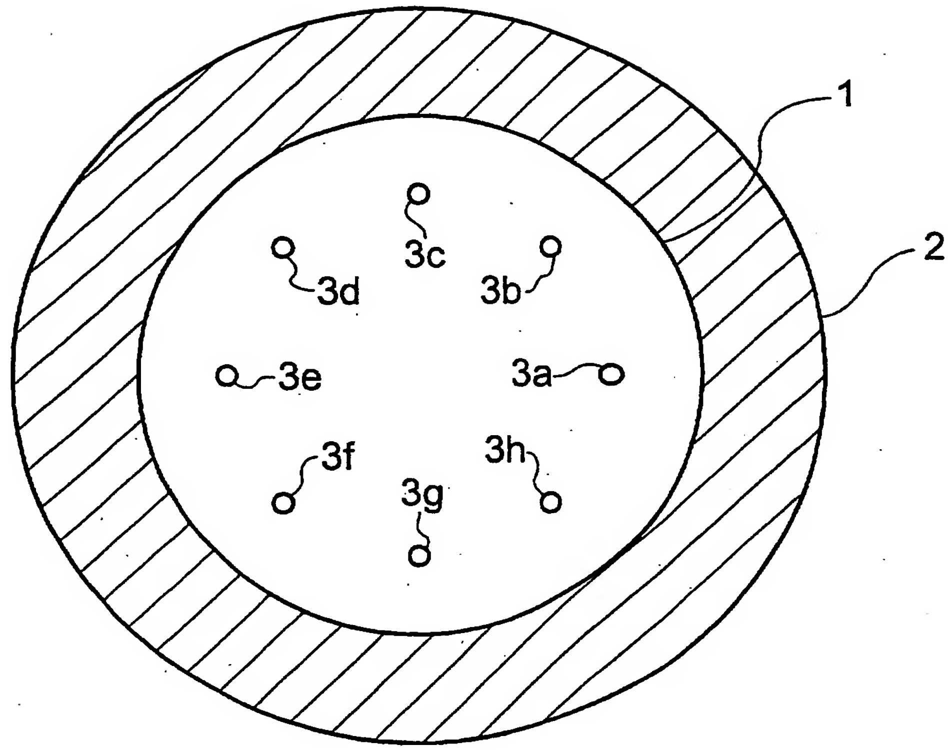



Fig. 1a

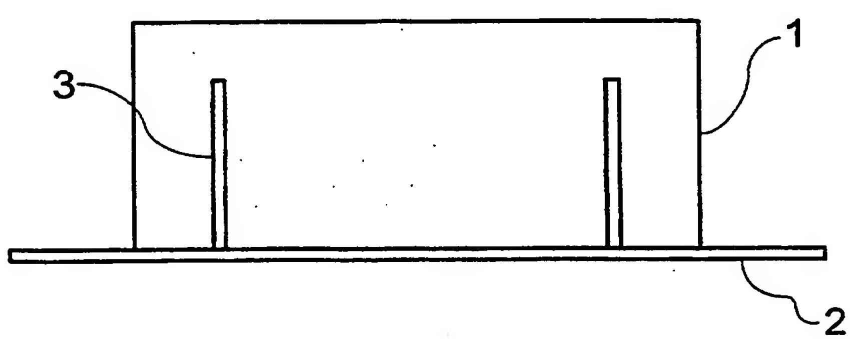



Fig. 1b

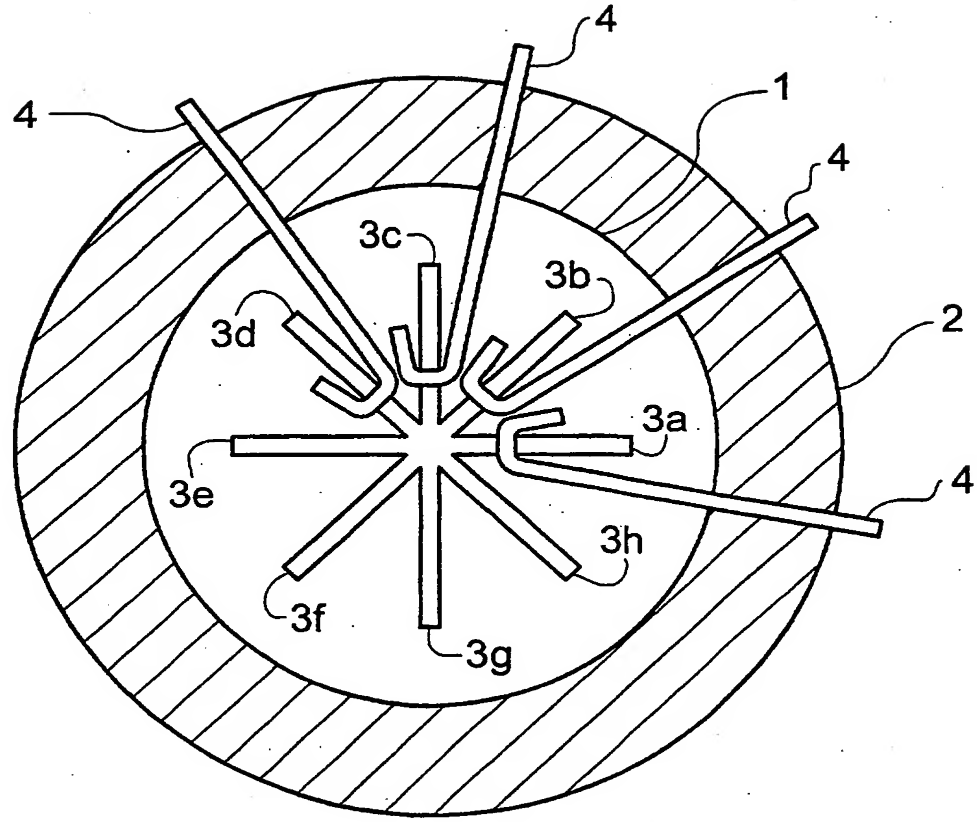



Fig. 2a

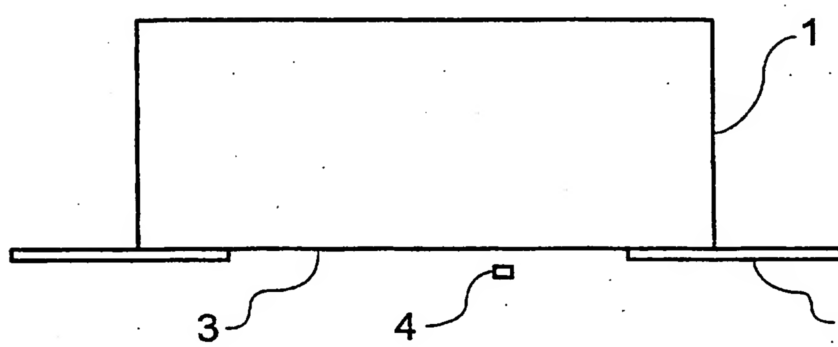



Fig. 2b

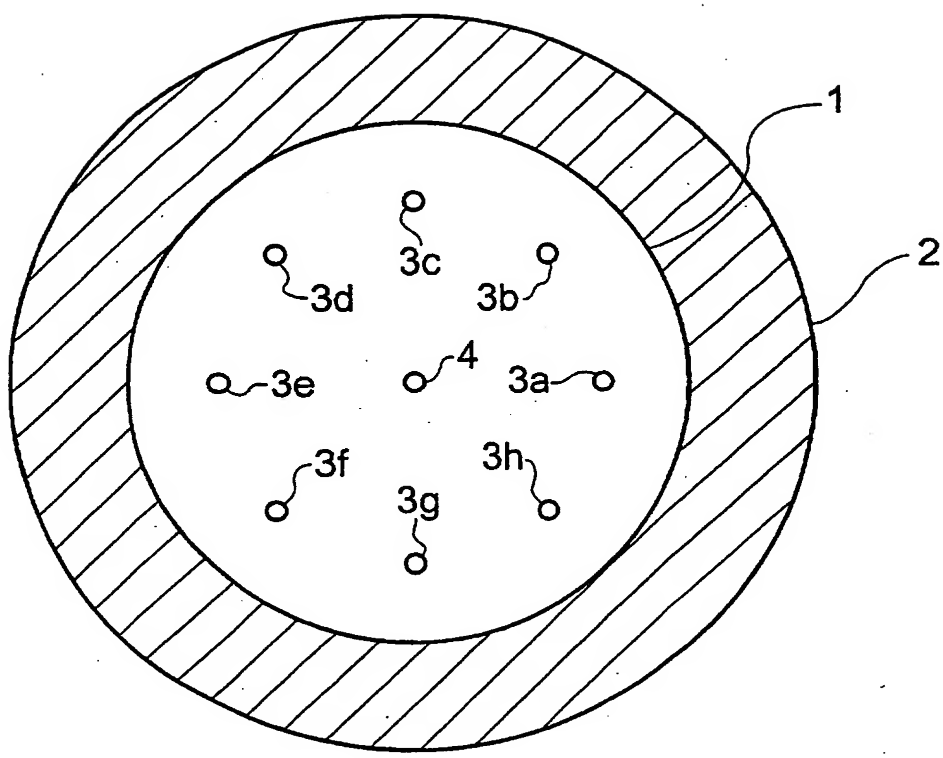



Fig. 3a

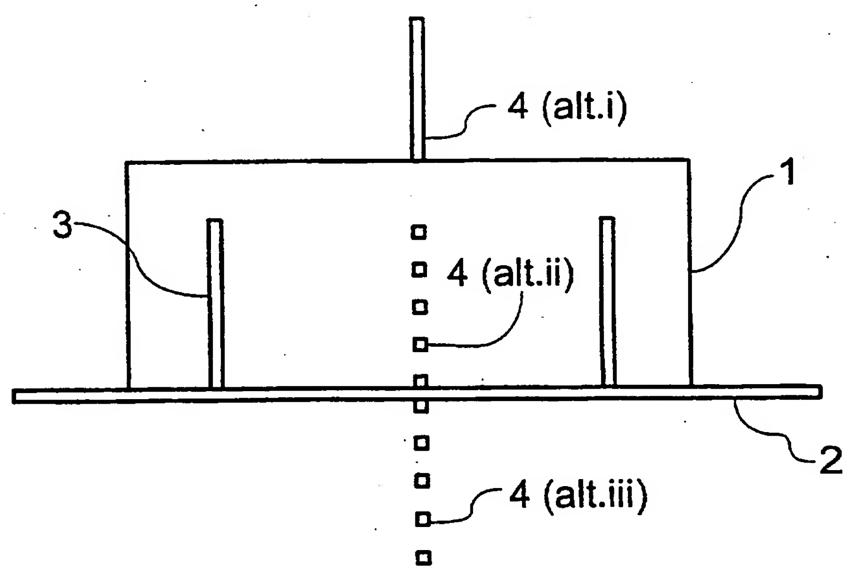



Fig. 3b

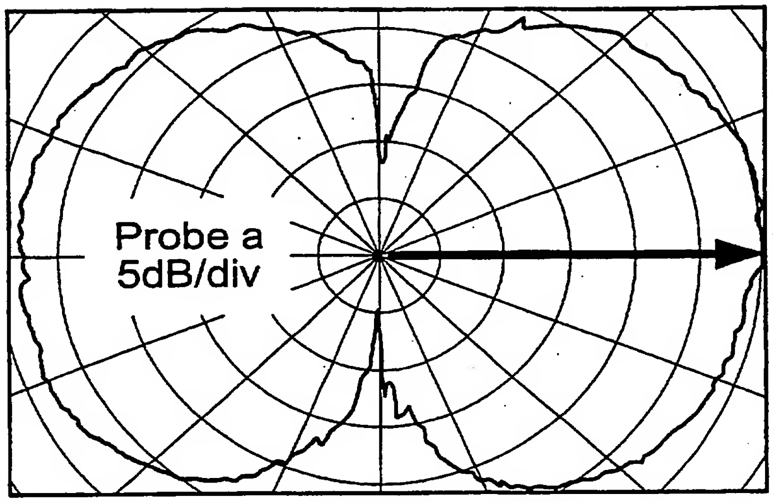



Fig. 4

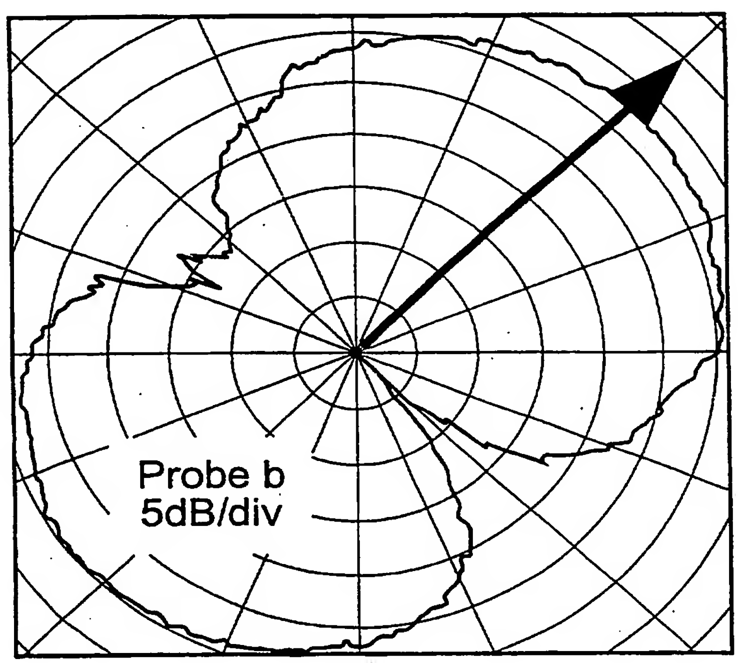



Fig. 5

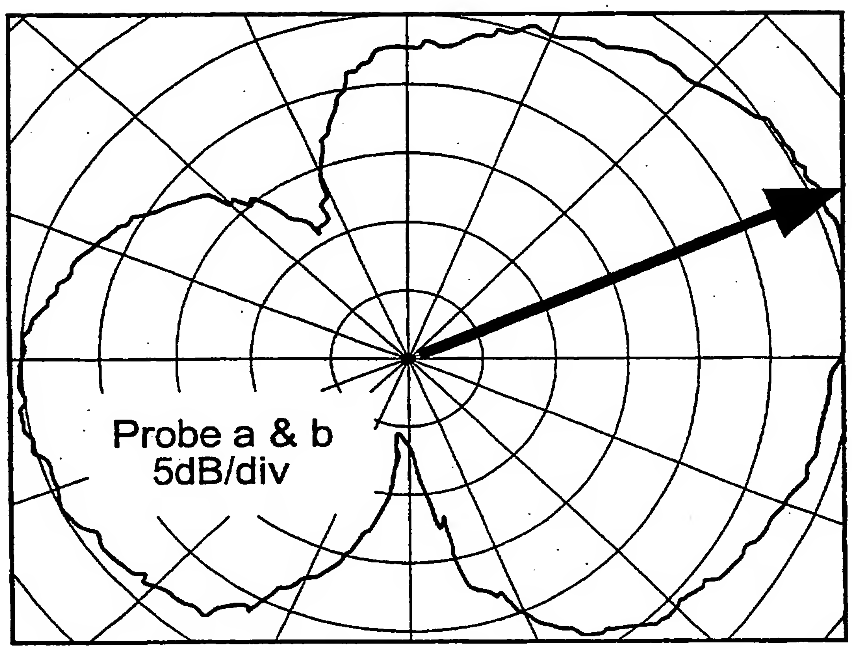



Fig. 6

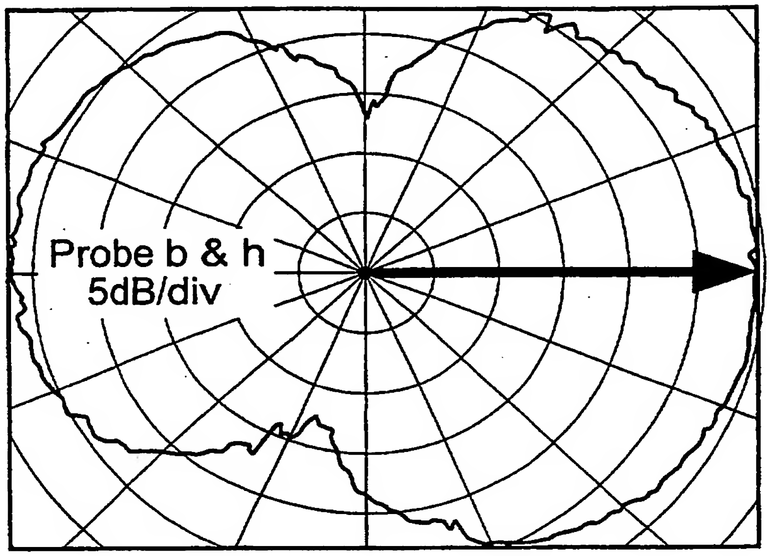



Fig. 7

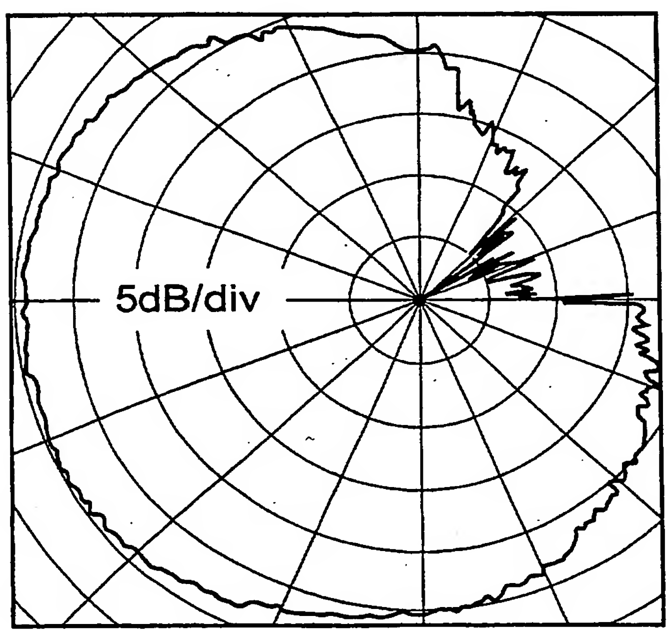



Fig. 8

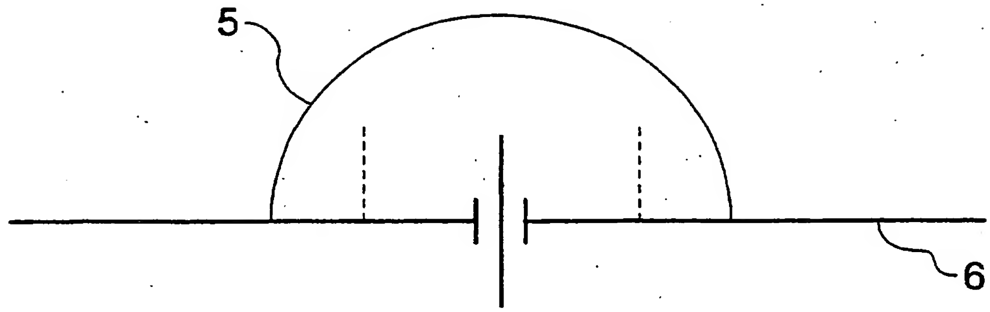



Fig. 9a

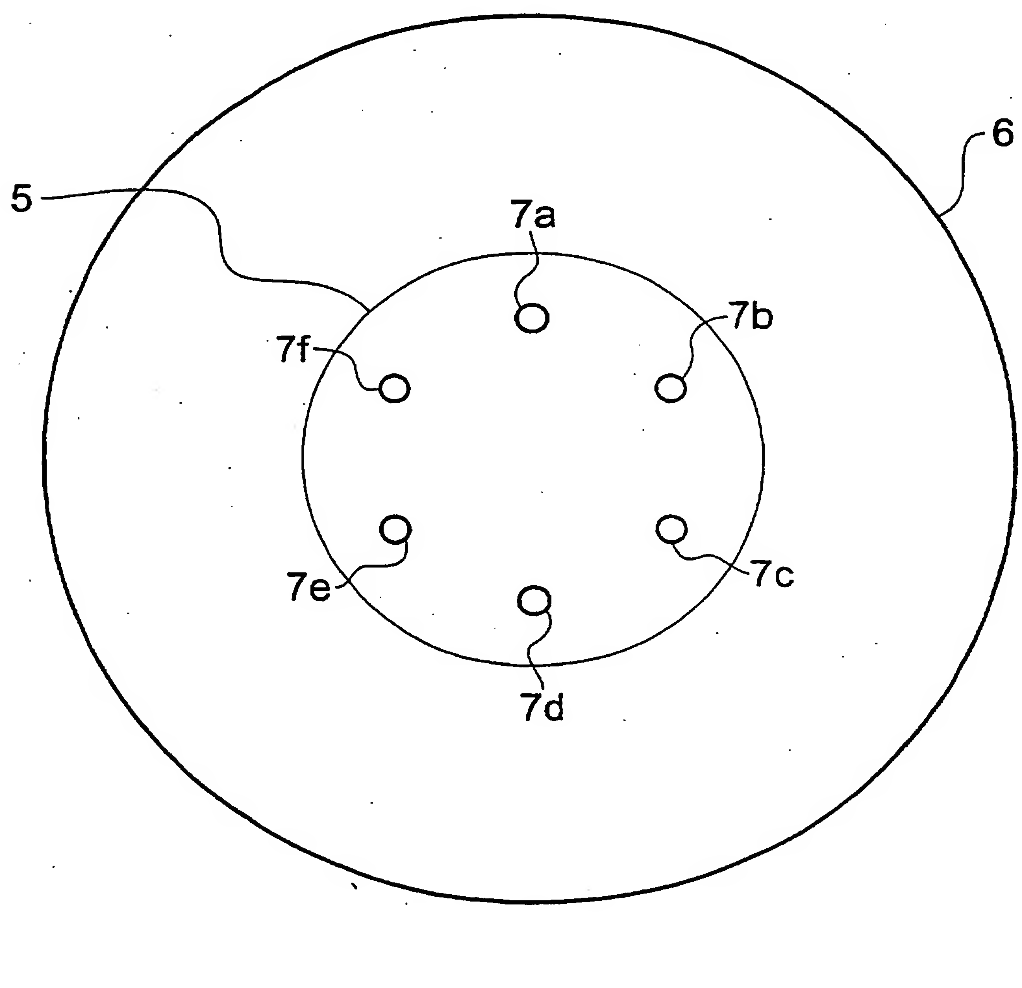
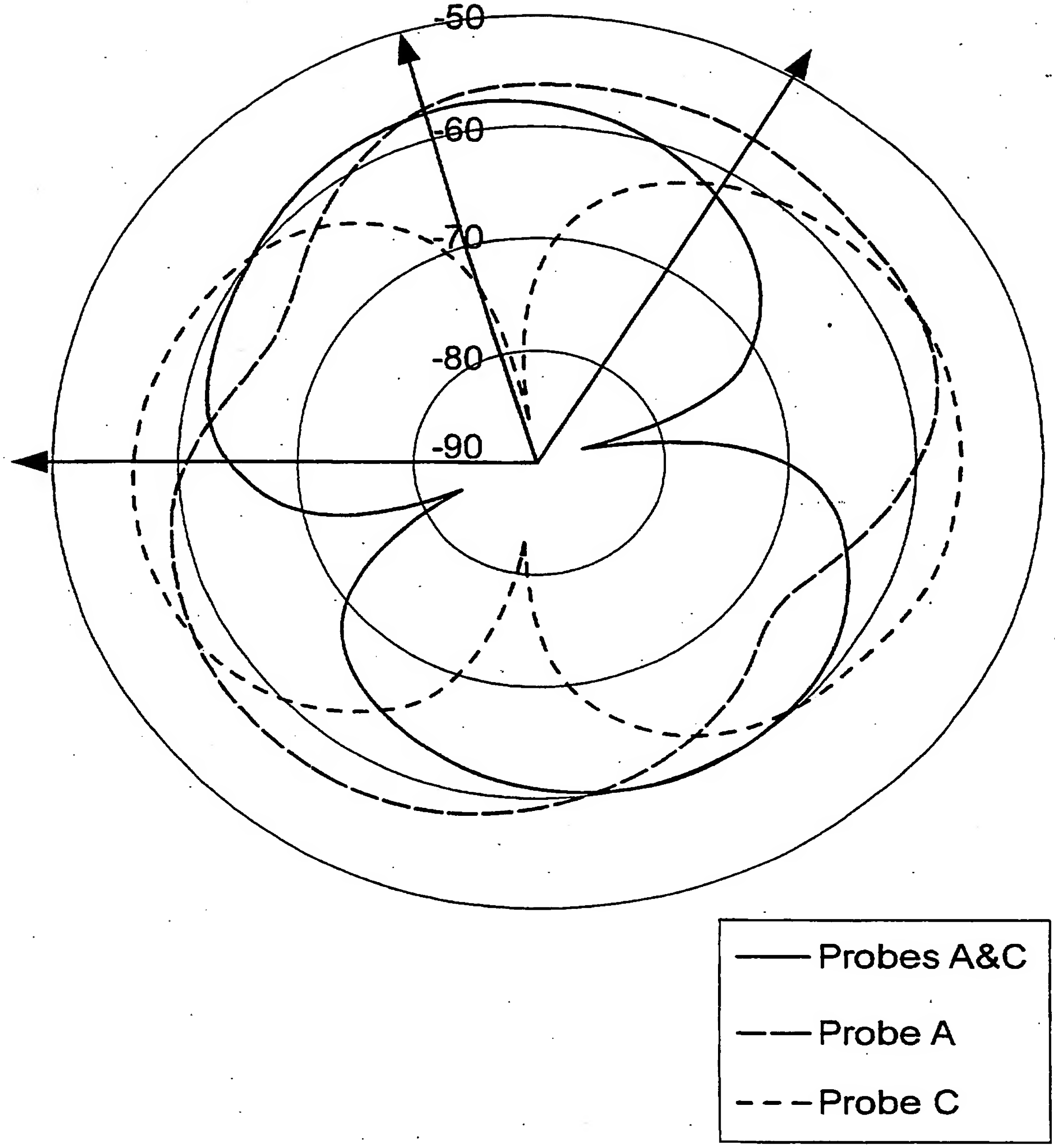



Fig. 9b




Hemispherical DRA 920MHz

Fig. 10

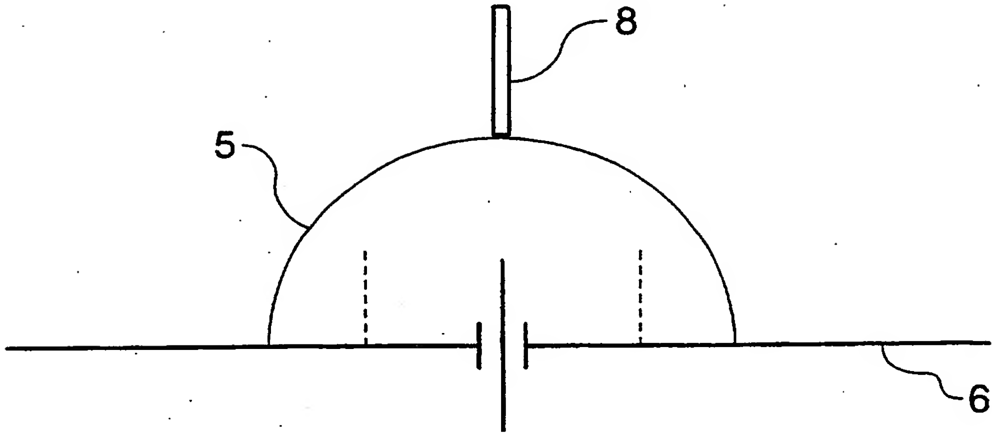



Fig. 11a

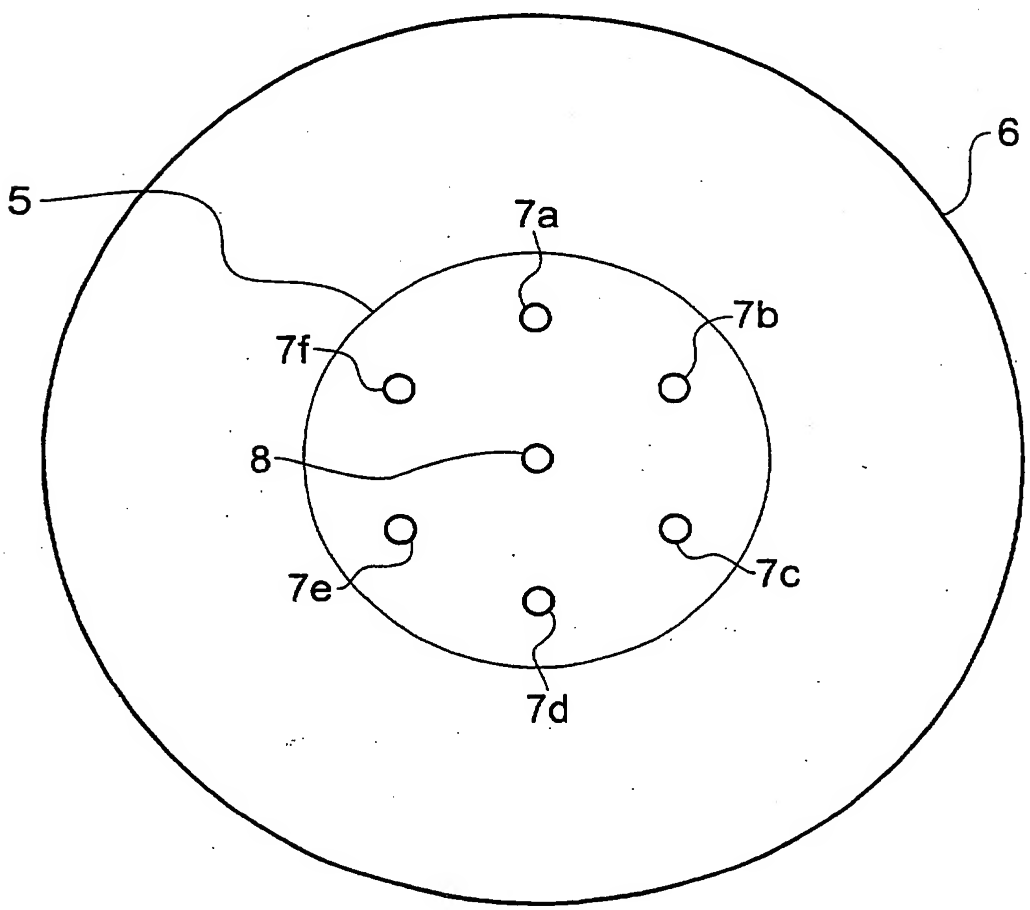



Fig. 11b

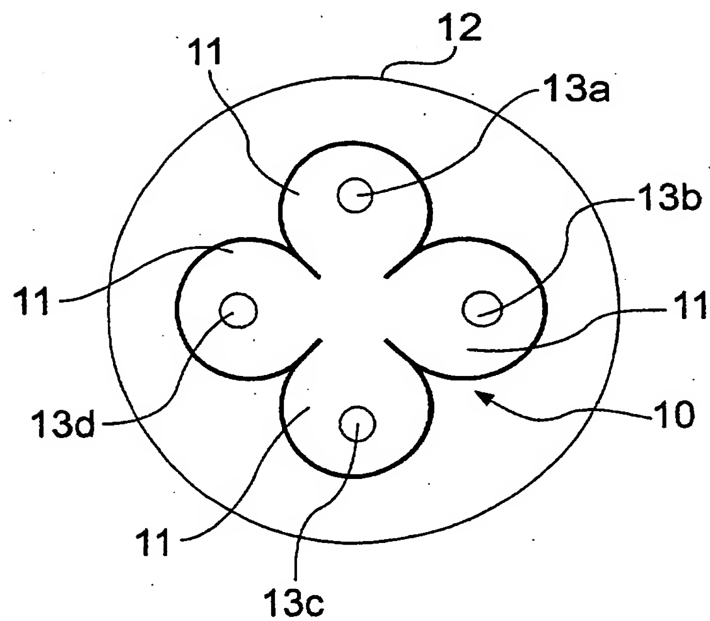



Fig. 12a

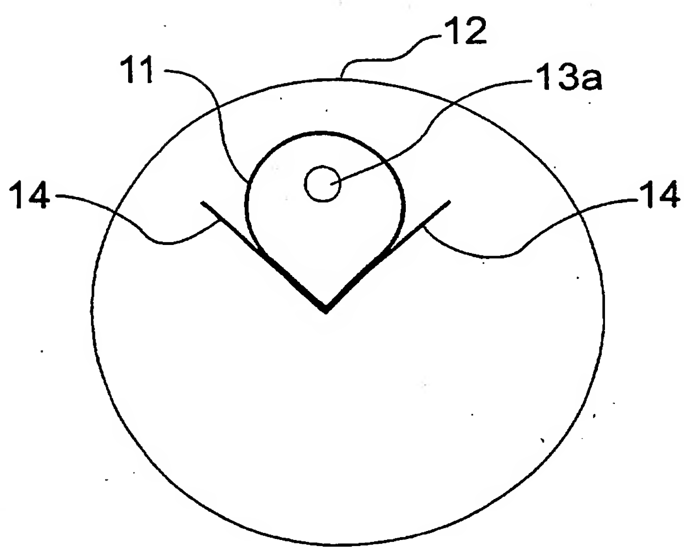
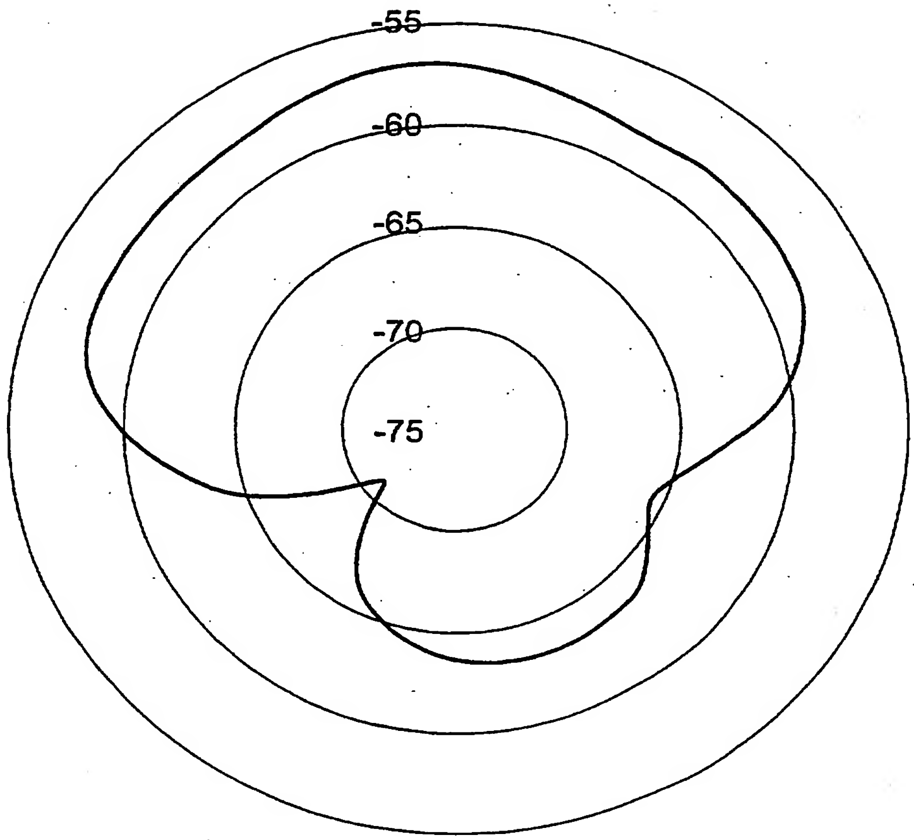



Fig. 12b




Quarter cloverleaf, 1378 MHz, bandwidth 169 MHz

Fig. 13

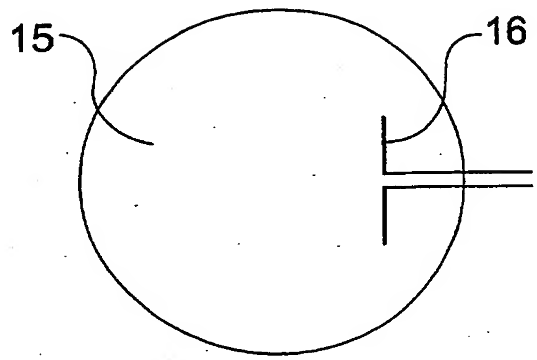



Fig. 14

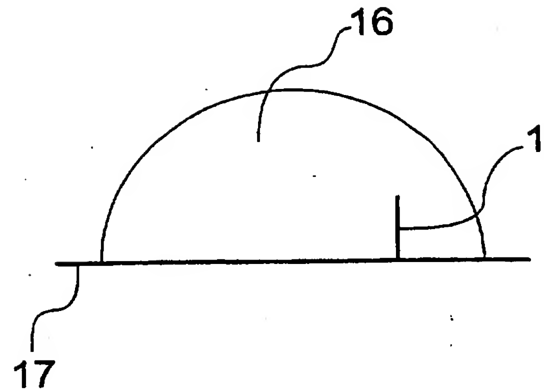



Fig. 15

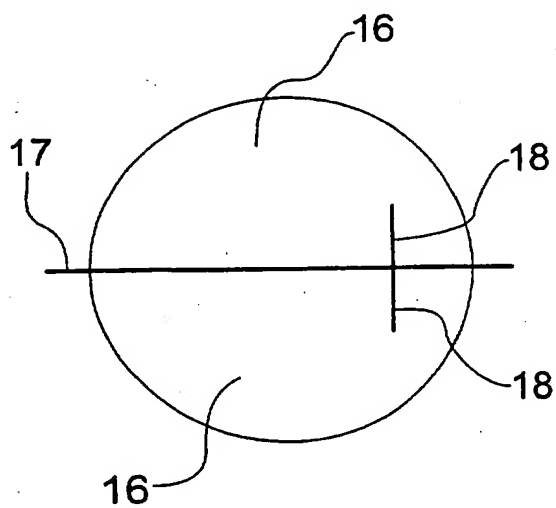



Fig. 16

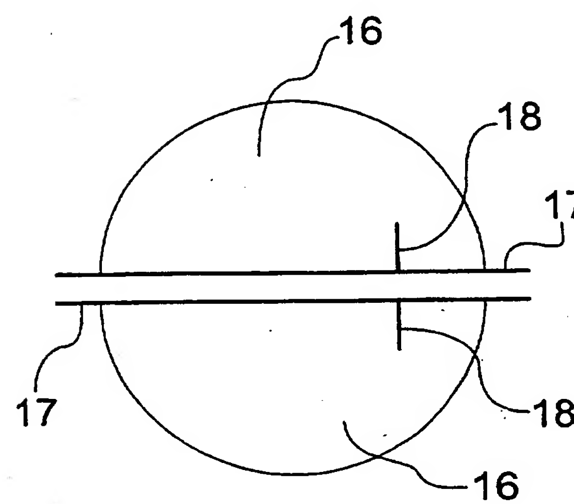



Fig. 17

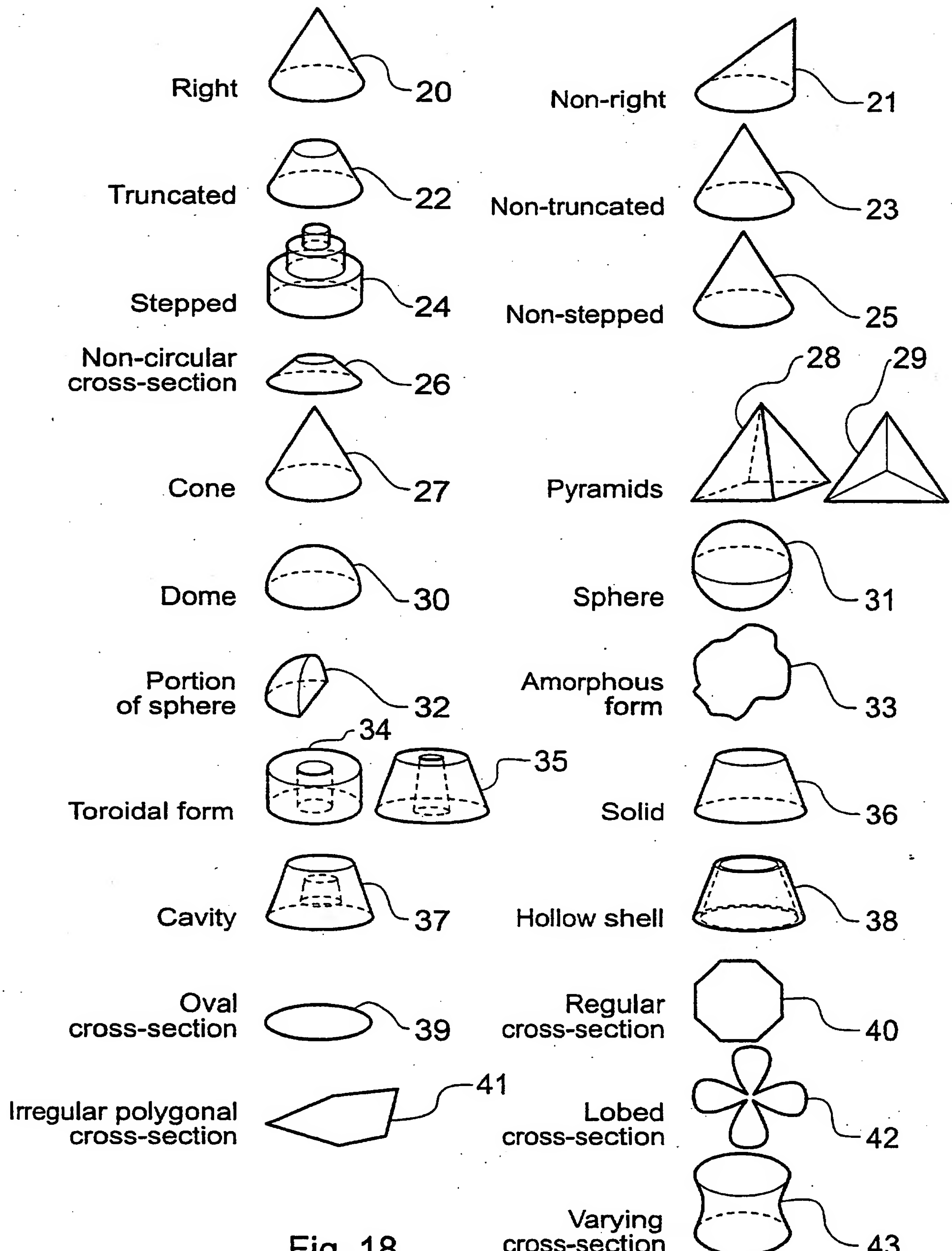

Right
20
Non-right
21
Truncated
22
Non-truncated
23
Stepped
24
Non-stepped
25
Non-circular cross-section
26
28
29
Cone
27
Pyramids
Dome
30
Sphere
31
Portion of sphere
32
Amorphous form
33
34
35
Toroidal form
Solid
36
Cavity
37
Hollow shell
38
Oval cross-section
39
Regular cross-section
40
41
Irregular polygonal cross-section
Lobed cross-section
42
Varying cross-section
43

Fig. 18

# STEERABLE-BEAM MULTIPLE-FEED DIELECTRIC RESONATOR ANTENNA OF VARIOUS CROSS-SECTIONS

This invention relates to dielectric resonator antennas with steerable receive and transmit beams and more particularly to an antenna having several separate feeds such that several separate beams can be created simultaneously and combined as desired, the dielectric resonator antenna including a dielectric resonator of various different cross-sections.

Since the first systematic study of dielectric resonator antennas (DRAs) in 1983 [LONG, S.A., McALLISTER, M.W., and SHEN, L.C.: 'The resonant cylindrical dielectric cavity antenna', IEEE Trans. Antennas Propagat., AP-31, 1983, pp 406-412], interest has grown in their radiation patterns because of their high radiation efficiency, good match to most commonly used transmission lines and their small physical size [MONGIA, R.K. and BHARTIA, P.: 'Dielectric resonator antennas - A review and general design relations for resonant frequency and bandwidth', Int. J. Microwave & Millimetre Wave Computer-Aided Engineering, 1994, 4, (3), pp 230-247]. Most configurations reported have used a slab of dielectric material mounted on a ground plane excited by either an aperture feed in the ground plane or by a probe inserted into the dielectric material. A few publications have reported on experiments using two probes fed simultaneously in a circular dielectric slab. These probes were installed on radials at 90° to each other and fed in anti-phase so as to create circular polarisation [MONGIA, R.K., ITTIPIBOON, A., CUHACI, M. and ROSCOE D.: 'Circular polarised dielectric resonator antenna', Electron. Lett., 1994, 30, (17), pp 1361-1362; and DROSSOS, G., WU, Z. and DAVIS, L.E.: 'Circular polarised cylindrical dielectric resonator antenna', Electron. Lett., 1996, 32, (4), pp 281-283.3, 4] and one publication included the concept of switching probes on and off [DROSSOS, G., WU, Z. and DAVIS, L.E.: 'Switchable cylindrical dielectric resonator antenna', Electron. Lett., 1996, 32, (10), pp 862-864].

One method of electronically steering an antenna pattern is to have a number of existing beams and to switch between them, or to combine them so as to achieve the

desired beam direction. A circular DRA may be fed by a single probe or aperture placed in or under the dielectric and tuned to excite a particular resonant mode. In preferred embodiments, the fundamental $HEM_{11\delta}$ mode is used, but there are many other resonant modes which produce beams that can be steered equally well using the apparatus of embodiments of the present invention. The preferred $HEM_{11\delta}$ mode is a hybrid electromagnetic resonance mode radiating like a horizontal magnetic dipole and giving rise to vertically polarised cosine or figure-of-eight shaped radiation pattern [LONG, S.A., McALLISTER, M.W., and SHEN, L.C.: 'The resonant cylindrical dielectric cavity antenna', IEEE Trans. Antennas Propagat., AP-31, 1983, pp 406-412]. Modelling by the present Applicants of cylindrical DRAs by FDTD (Finite Difference Time Domain) and practical experimentation has shown that if several such probes are inserted into the dielectric and one is driven whilst all the others are open-circuit then the beam direction can be moved by switching different probes in and out. Furthermore, by combining feeds in different ways, sum and difference patterns can be produced which allow continuous beam-steering and direction finding by amplitude-comparison, monopulse or similar techniques.

Many of these results are described in the present inventors' co-pending US patent application serial no 09/431,548 and in the paper KINGSLEY, S.P. and O'KEEFE, S.G., "Beam steering and monopulse processing of probe-fed dielectric resonator antennas", S P Kingsley and S G O'Keefe, IEE proceedings - Radar Sonar and Navigation, 146, 3, 121 - 125, 1999, the disclosures of which are incorporated into the present application by reference.

It has been noted by the present applicants that the results described in the above reference apply equally to DRAs operating at any of a wide range of frequencies, for example from 1 MHz to 100,000 MHz and even higher for optical DRAs. The higher the frequency in question, the smaller the size of the DRA, but the general beam patterns achieved by the probe/aperture geometries described hereinafter remain generally the same throughout any given frequency range. Operation at frequencies substantially below 1MHz is possible too, using dielectric materials with a high dielectric constant.

The concept of hemispherical dielectric resonator antennas is known from [McALLISTER, M.W. & LONG, S.A.: "Resonant hemispherical dielectric antenna", Electronics Letters, 1984, **20**, (16), pp 657-659; MONGIA, R.K. and BHARTIA, P.: "Dielectric Resonator Antennas - A Review and General Design Relations for Resonant Frequency and Bandwidth", International Journal of Microwave and Millimetre-Wave Computer-Aided Engineering, 1994, **4**, (3), pp 230-247; and KISHK, A.A., ZHOU, G. & GLISSON, A.W.: "Analysis of dielectric resonator antennas with emphasis on hemispherical structures", IEEE Antennas Propag. Mag., 1994, 36, pp 20-31]. These references make no mention of hemispherical dielectric resonator antennas with a plurality of probes or steerable receive and transmit beams.

A hemispherical dielectric resonator antenna has the advantage of a simple spherical interface between itself and free space [LEUNG, K.W., LUK, K.M., LAI, K.Y.A. & LIN, D.: "Theory and experiment of a co-axial probe fed hemispherical dielectric resonator antenna", IEEE Transactions on Antennas and Propagation, AP-41, 1993, pp 1390-1398] and of being capable of being rigorously analysed which simplifies design procedures [LEUNG, K.W., NG, K.W. LUK, K.M. & YUNG, E.K.N., "Simple formula for analysing the centre-fed hemispherical dielectric resonator antenna", Electronics Letters, 1997, **33**, (6)].

According to a first aspect of the present invention, there is provided a dielectric resonator antenna including a grounded substrate, a dielectric resonator disposed on the grounded substrate and a plurality of feeds for transferring energy into and from different regions of the dielectric resonator, the feeds being activatable individually or in combination so as to produce at least one incrementally or continuously steerable beam which may be steered through a predetermined angle, characterised in that the dielectric resonator has a cross-section that varies along an axis extending substantially perpendicularly from the grounded substrate.

It will be appreciated that where the grounded substrate is other than substantially planar, then the axis may be defined as substantially perpendicular to a plane which is tangential to a surface of the grounded substrate at a point from where the axis is taken. The cross-section may vary in size or in shape or in both size and shape along the axis.

Advantageously, the dielectric resonator antenna includes electronic circuitry adapted to activate the feeds individually or in combination so as to produce at least one incrementally or continuously steerable beam which may be steered through a predetermined angle.

In a first embodiment, the dielectric resonator has the form of a cone or a truncated cone. The cone may be a right cone or a non-right cone, and may be configured such that its cross-section increases or decreases in area along the axis. In comparison to a dielectric resonator antenna including a resonator of constant cross-section, such conical resonators may have increased bandwidth and, in the case of non-right conical resonators, may allow a generated beam pattern to vary about the axis.

In a second embodiment, the dielectric resonator has the form of a pyramid or a truncated pyramid. The pyramid may be a right pyramid or a non-right pyramid, and may be configured such that its cross-section increases or decreases in area along the axis. The pyramid may be a 3-pyramid, a 4-pyramid, a 5-pyramid or an n-pyramid, where n is a positive integer. In comparison to a dielectric resonator antenna including a resonator of constant cross-section, such pyramidal resonators may have increased bandwidth and, in the case of non-right conical resonators, may allow a generated beam pattern to vary about the axis. Furthermore, it has been found that an oblong resonator has two resonant frequencies associated with the dimensions of the two differently-sized sides. Accordingly, it is expected that a resonator having a greater number of differently-sized sides will have a greater number of resonant frequencies. These resonant frequencies may be selected to be closely spaced so as to increase bandwidth, or to be widely spaced so as to permit operation in different frequency bands.

In a third embodiment, the dielectric resonator has the form of a stepped cone or pyramid or a truncated stepped cone or pyramid. The term 'stepped' is here intended to mean a structure of generally conical or pyramidal shape having a surface which is not even, such as a Tower of Hanoi structure corresponding in external shape to a stack of discs of diminishing diameter. The stepped cone or pyramid may be a right stepped cone or pyramid or a non-right stepped cone or pyramid, and may be configured such that its cross-section increases or decreases in area along the axis. In comparison to a dielectric resonator antenna including a resonator of constant cross-section, such stepped conical or pyramidal resonators may have increased bandwidth and, in the case of non-right stepped conical or pyramidal resonators, may allow a generated beam pattern to vary about the axis.

In a fourth embodiment, the dielectric resonator is generally dome shaped or has the form of a sphere or a portion of a sphere. For example, the resonator may be substantially spherical, hemispherical, semihemispherical, semidemihemispherical or the like. Alternatively, the resonator may have the form of an arbitrary segment of a sphere. Such shapes allow beamsteering in three-dimensions from the curved surface portion of the resonator.

A substantially spherical resonator may be made up of two substantially hemispherical resonator elements, each contacting a grounded substrate and fed by monopole feeds. The hemispherical elements may be joined together on either side of a shared grounded substrate so as to make a substantially spherical resonator, or may each be provided with a separate grounded substrate at their base portions and then placed close to each other so as to make a substantially spherical resonator.

A further advantage of these embodiments is that rounded resonators tend to be shaped more aerodynamically than, say, a cylindrical resonator, which is advantageous when a dielectric resonator antenna is to be mounted on an outer surface of an aircraft, for example.

In a fifth embodiment, the dielectric resonator is amorphous, i.e. of irregular or indeterminate shape. For example, the resonator may be formed as an amorphous mass of dielectric gel or other appropriate dielectric material such as a plastics material. Subject to operating requirements, such an amorphous resonator may be moulded as part of a structure such as a casing for a mobile telephone or other communications device.

In a sixth embodiment, the dielectric resonator is annular with a hollow centre (in the manner of a "Gugelhupf" cake, which has a generally toroidal structure having an overall dome-shaped profile). Such a structure may be substantially lighter and use less dielectric material than a solid dielectric resonator. The resonator may have a base perimeter which is circular, oval or any other appropriate shape. As with the previously discussed embodiments, geometries of non-circular cross-section generally confer the advantage of broad bandwidth operation.

According to a second aspect of the present invention, there is provided a dielectric resonator antenna including a grounded substrate, a dielectric resonator disposed on the grounded substrate and a plurality of feeds for transferring energy into and from different regions of the dielectric resonator, the feeds being activatable individually or in combination so as to produce at least one incrementally or continuously steerable beam which may be steered through a predetermined angle, characterised in that the dielectric resonator has a non-circular cross-section.

Advantageously, the dielectric resonator antenna includes electronic circuitry adapted to activate the feeds individually or in combination so as to produce at least one incrementally or continuously steerable beam which may be steered through a predetermined angle.

The dielectric resonator may have a substantially oval cross-section, a regular or irregular polygonal cross-section, a lobed cross-section, or any other appropriate non-circular cross-section. These cross-sections generally allow the dielectric resonator to be lighter and to use less dielectric material than an equivalent size

cylindrical resonator of truly circular cross-section. Non-circular cross-sections generally also provide better bandwidth and, when constructed in segmented form, may have low backlobes in predetermined directions. The cross-section of the dielectric resonator may be substantially constant along an axis extending substantially perpendicularly from the grounded substrate or may vary, either in size or in shape or in both size and shape.

According to a third aspect of the present invention, there is provided a dielectric resonator antenna including a dielectric resonator and at least one dipole feed for transferring energy into and from the dielectric resonator, the dipole feed having a longitudinal axis and being activatable so as to produce at least one incrementally or continuously steerable beam which may be steered through a predetermined angle, characterised in that the dielectric resonator has a cross-section that varies along an axis extending substantially parallel to the axis of the dipole feed.

The dielectric resonator may be in the form of a substantially solid sphere of a dielectric material which is fed by at least one and preferably more than one dipole probe and which does not need a grounded substrate. Such a resonator enables three-dimensional coverage over the whole sphere since there is no groundplane. Indeed, a dipole feed may be used to drive any shape of dielectric resonator without the need for a grounded substrate. Where monopole feeds and a grounded substrate are used, the grounded substrate acts as a mirror plane in which the dielectric resonator sees its mirror image. An equivalent dielectric resonator antenna may be manufactured by providing a dielectric resonator having a shape corresponding to the shape of the monopole feed embodiment and its image as reflected in the plane of the grounded substrate. As stated above, there is then no need for a grounded substrate in the dipole feed embodiment. In general, however, the monopole feed embodiment is preferred, since it is easier to use a monopole feed inserted into a half-shape dielectric resonator disposed on a grounded substrate than it is to embed a dipole probe and feed cable within a whole shape dielectric resonator.

The substantially spherical dielectric resonator will generally be made up of two hemispherical portions which are stuck together so as to sandwich the at least one dipole feed between base portions thereof.

According to a fourth aspect of the present invention, there is provided a dielectric resonator antenna including a dielectric resonator and at least one dipole feed for transferring energy into and from different regions of the dielectric resonator, the dipole feed being activatable so as to produce at least one incrementally or continuously steerable beam which may be steered through a predetermined angle, characterised in that the dielectric resonator has a non-circular cross-section.

The dipole feed preferably has a longitudinal axis, and the cross-section of the dielectric resonator is preferably defined as being substantially perpendicular to that axis.

It will be appreciated that equivalents to any of the dielectric resonator shapes described above in relation to the grounded substrate embodiment may be made with the dipole embodiment by providing a dielectric resonator equivalent in shape to that of the grounded substrate embodiment together with its reflection in the plane of the grounded substrate.

In all of the embodiments described above, the dielectric resonator may be substantially solid or may alternatively include at least one cavity therein. In some applications, the dielectric resonator may be in the form of a hollow shell of the desired shape.

Advantageously, the antenna of the present invention is adapted to produce at least one incrementally or continuously steerable beam which may be steered through a complete 360 degree circle.

Advantageously, there is additionally or alternatively provided electronic circuitry to combine the feeds to form sum and difference patterns to permit radio direction finding capability of up to 360 degrees.

The electronic circuitry may additionally or alternatively be adapted to combine the feeds to form amplitude or phase comparison radio direction finding capability of up to 360 degrees.

Preferably, radio direction finding capability is a complete 360 degree circle.

The feeds may take the form of conductive probes which are contained within or placed against the dielectric resonator or may comprise aperture feeds provided in the grounded substrate (these are not appropriate for the dipole embodiment). Aperture feeds are discontinuities (generally rectangular in shape) in the grounded substrate underneath the dielectric material and are generally excited by passing a microstrip transmission line beneath them. The microstrip transmission line is usually printed on the underside of the substrate. Where the feeds take the form of probes, these may be generally elongate in form. Examples of useful probes include thin cylindrical wires which are generally parallel to a longitudinal axis of the dielectric resonator. Other probe shapes that might be used (and have been tested) include fat cylinders, non-circular cross sections, thin generally vertical plates and even thin generally vertical wires with conducting 'hats' on top (like toadstools). Probes may also comprise metallised strips placed within or against the dielectric. In general any conducting element within or against the dielectric resonator will excite resonance if positioned, sized and fed correctly. The different probe shapes give rise to different bandwidths of resonance and may be disposed in various positions and orientations (at different distances along a radius from the centre and at different angles from the centre, as viewed from above) within or against the dielectric resonator so as to suit particular circumstances.

Where more than feed is provided, different feeds can be driven at different frequencies so as to make the antenna transmit or receive simultaneously in different predetermined directions (e.g. azimuth and in elevation) at the different frequencies.

Furthermore, there may be provided probes within or against the dielectric resonator which are not connected to the electronic circuitry but instead take a passive role in influencing the transmit/receive characteristics of the dynamic resonator antenna, for example by way of induction.

In one embodiment of the present invention, the dielectric resonator may be divided into segments by conducting walls provided therein, as described, for example, in TAM, M.T.K. AND MURCH, R.D., 'Compact circular sector and annular sector dielectric resonator antennas', IEEE Trans. Antennas Propagat., AP-47, 1999, pp 837-842.

In a further embodiment of the present invention, there may additionally be provided an internal or external monopole antenna which is combined with the dielectric resonator antenna so as to cancel out backlobe fields or to resolve any front/back ambiguity which may occur with a dielectric resonator antenna having a cosine or 'figure of eight' radiation pattern. The monopole antenna may be centrally-disposed within the dielectric resonator or may be mounted thereupon or therebelow and is activatable by the electronic circuitry. In embodiments including an annular resonator with a hollow centre, the monopole could be located within the hollow centre. A "virtual" monopole may also be formed by the electrical or algorithmic combination of any probes or apertures, preferably a symmetrical set of probes or apertures.

The dielectric resonator antenna and antenna system of the present invention may be operated with a plurality of transmitters or receivers, these terms here being used to denote respectively a device acting as source of electronic signals for transmission by way of the antenna or a device acting to receive and process electronic signals communicated to the antenna by way of electromagnetic radiation. The number of

transmitters and/or receivers may or may not be equal to the number of feeds to the dielectric resonator. For example, a separate transmitter and/or receiver may be connected to each feed (i.e. one per feed), or a single transmitter and/or receiver to a single feed (i.e. a single transmitter and/or receiver is switched between feeds). In a further example, a single transmitter and/or receiver may be (simultaneously) connected to a plurality of feeds – by continuously varying the feed power between the feeds the beam and/or directional sensitivity of the antenna may be continuously steered. A single transmitter and/or receiver may alternatively be connected to several non-adjacent feeds to the dielectric resonator, thereby enabling a significant increase in bandwidth to be attained as compared with a single feed (this is advantageous because DRAs generally have narrow bandwidths). In yet another example, a single transmitter and/or receiver may be connected to several adjacent or non-adjacent feeds in order to produce an increase in the generated or detected radiation pattern, or to allow the antenna to radiate or receive in several directions simultaneously.

The dielectric resonator may be formed of any suitable dielectric material, or a combination of different dielectric materials, having an overall positive dielectric constant k; in preferred embodiments, k is at least 10 and may be at least 50 or even at least 100. k may even be very large e.g. greater than 1000, although available dielectric materials tend to limit such use to low frequencies. The dielectric material may include materials in liquid, solid or gas states, or any intermediate state. The dielectric material could be of lower dielectric constant than a surrounding material in which it is embedded.

By seeking to provide a dielectric resonator antenna capable of generating multiple beams which can be selected separately or formed simultaneously and combined in different ways at will, embodiments of the present invention may provide the following advantages:

i) By choosing to drive different probes or apertures, the antenna can be made to transmit or receive in one of a number of preselected directions (in azimuth, for

example). By sequentially switching round the probes or apertures the beam pattern can be made to rotate incrementally in angle. Such beam-steering has obvious applications for radio communications, radar and navigation systems.

ii) By combining two or more beams together, i.e. exciting two or more probes or apertures simultaneously, beams can be formed in any arbitrary azimuth direction, thus giving more precise control over the beamforming process.

iii) By electronically continuously varying the power division /combination between two beams, the resultant combination beam direction can be steered continuously.

iv) On receive-only, the direction of arrival of an incoming radio signal can be found by comparing the amplitude of the signal on two or more beams, or by carrying out monopulse processing of the signal received on two beams. 'Monopulse processing' refers to the process of forming sum and difference patterns from two beams so as to determine the direction of arrival of a signal from a distant radio source.

v) In a typical two-way communication system (such as a mobile telephone system) signals are received (by a handset) from a point radio source (such as a base station) and transmitted back to that source. Embodiments of the present invention may be used to find the direction of the source using step iii) above and may then form an optimal beam in that direction using step ii). An antenna capable of performing this type of operation is known as a 'smart' or 'intelligent' antenna. The advantages of the maximum antenna gain offered by smart antennas is that the signal to noise ratio is improved, communications quality is improved, less transmitter power may be used (which can, for example, help to reduce irradiation of any nearby human body) and battery life is conserved.

vi) The addition of an internal or external monopole antenna can be used to null out the backlobe of the antenna, thereby reducing the irradiation of a person near the device, or to resolve front/back ambiguities in radio direction finding.

vii) By choosing to drive different feeds (probes or apertures) at different frequencies, the antenna can be made to transmit or receive simultaneously in one predetermined direction (in azimuth, for example) on one frequency in other predetermined directions on other frequencies.

For a better understanding of the present invention and to show how it may be carried into effect, reference shall now be made by way of example to the accompanying drawings, in which:

FIGURE 1a is a top view of an existing multi-feed dielectric resonator antenna using probe feeds;

FIGURE 1b is a side view of the multi-feed dielectric resonator antenna of Figure 1a;

FIGURE 2a is a top view of an existing multi-feed dielectric resonator antenna using aperture feeds;

FIGURE 2b is a side view of the multi-feed dielectric resonator antenna of Figure 2a;

FIGURE 3a is a top view of an existing multi-probe dielectric resonator antenna with the addition of a central monopole;

FIGURE 3b is a side view of the multi-probe dielectric resonator of Figure 3a;

FIGURES 4 to 7 show measured azimuth radiation patterns for the antenna of Figures 1a and 1b as various combinations of probes are driven;

FIGURE 8 shows a measured azimuth radiation pattern for the antenna of Figures 3a and 3b as it is simultaneously driven with a monopole antenna;

FIGURE 9a is a side view of a generalised multi-feed hemispherical dielectric resonator antenna of the present invention using probe feeds;

FIGURE 9b is a top view of the multi-feed hemispherical dielectric resonator antenna of Figure 9a;

FIGURE 10 shows measured azimuth radiation patterns for the antenna of Figures 9a and 9b for probes 7a, 7c, and 7a and 7c simultaneously;

FIGURE 11a is a side view of a generalised multi-feed hemispherical dielectric resonator antenna of the present invention using probe feeds and a central monopole antenna;

FIGURE 11b is a top view of the multi-feed hemispherical dielectric resonator antenna of Figure 11a;

FIGURE 12a is cross-sectional view on a segmented multi-feed dielectric resonator antenna made up of four lobes;

FIGURE 12b is a cross-sectional view on a dielectric resonator antenna formed from a single lobe of the Figure 12a embodiment;

FIGURE 13 shows the measured azimuth pattern for a single lobe of the dielectric resonator antenna of Figure 12;

FIGURES 14 to 17 show various spherical and hemispherical dielectric resonator antennas according to the present invention; and

FIGURE 18 shows various shapes of dielectric resonator that may be used in the present invention.

Figures 1 to 8 relate mainly to a dielectric resonator antenna having a cylindrical shape as described, for example, in co-pending US patent application serial no 09/431,548 from which the present application claims priority.

Referring now to Figures 1a and 1b, there is shown a substantially circular slab of dielectric material 1 which is disposed on a grounded substrate 2 having a plurality of holes to allow access by cables and connectors to a plurality of internal probes 3a to 3h. The probes 3a to 3h are disposed along radii at different internal angles.

Figures 2a and 2b show a substantially circular slab of dielectric material 1 which is disposed on a grounded substrate 2 having a plurality of aperture feeds 3a to 3h disposed along radii at different internal angles. The aperture feeds are fed by microstrip transmission lines 4.

Figures 3a and 3b show side plan and side views respectively, as for Figures 1a and 1b, but with the addition of a central monopole antenna 4(i) above the dielectric slab 1 used to cancel out the backlobe or resolve the front/back ambiguity that occurs with dynamic resonator antennas having cosine or 'figure of eight radiation' patterns. In Figure 3 the monopole 4(i) is shown as an external device above the dielectric slab 1, but a central probe 4(ii) within the dielectric slab 1 will also act as a suitable monopole reference antenna, as will a central probe 4(iii) below the slab 1.

The basic concept for a multiple-beam dielectric resonator antenna using a plurality of feeds is given by the present Applicants in the paper KINGSLEY, S.P. and O'KEEFE, S.G., "Beam steering and monopulse processing of probe-fed dielectric resonator antennas", S P Kingsley and S G O'Keefe, IEE proceedings - Radar Sonar and Navigation, 146, 3, 121 - 125, 1999. This paper confirms by practical experimentation the present Applicants' FDTD simulation results that multiple-feed

operation is possible and that the feeds do not mutually interact electrically in any significant way that prevents the formation of several beams simultaneously.

Since the publication of this paper an 8-probe circular dielectric resonator antenna, having the form shown in Figures 1a and 1b has been constructed and tested. In a further development, an 8-probe circular dielectric resonator antenna with an external monopole antenna, having the form shown in Figs 3a & 3b, has also been constructed and tested.

In Figures 4-8, the circular lines represent power steps of 5 dB (decibels) and the arrow shows the direction of the principal beam direction or 'boresight'. The radial lines represent the angle of the beam; this being the azimuth direction when the antenna is placed on a horizontal plane.

Results are given here for a cylindrical dielectric resonator antenna fitted with 8 internal probes 3a to 3h disposed in a circle. When probe 3a is driven (in either transmit or receive mode) and the remaining probes 3b to 3h are open-circuited or otherwise terminated, but not connected to the feed, then the measured azimuth radiation pattern shown in Figure 4 is obtained.

When probe 3b is connected instead of probe 3a, the measured azimuth radiation pattern is as shown in Figure 5. It can be seen that the beam has been steered incrementally by roughly the same angle as the probes are disposed internally (45 degrees in this case).

When probes 3a and 3b are driven simultaneously with equal power from a single source, using a power splitter/divider or similar power sharing device and with the remaining 6 probes open-circuited, the resulting measured azimuth radiation pattern is as shown in Figure 6. It can be seen that the beam has been steered roughly to an angle between the angles by which the probes are disposed internally (22.5 degrees in this case). This method can be used to continuously steer the beam by continuously varying the feed power being shared between probes. For example,

where the power splitter is operated in such a way so as incrementally to transfer power from probe 3a to 3b, the direction of the transmitted or received beam will be steered correspondingly in proportion to the transfer of power. As the entire azimuth radiation pattern rotates with the beam, the direction of any nulls also changes in a corresponding fashion. In many applications (e.g. missile tracking) it is the null or nulls which are used rather than the beam or beams, particularly since antennas of this type can be made to have deep nulls.

If probes 3b and 3h are driven simultaneously with the remaining 6 probes being open-circuited, this should produce an azimuth radiation pattern with a boresight (that is, a direction of maximum radiation on transmit, or a direction of maximum sensitivity on receive) in the same direction as probe 3a (probes 3b and 3h being disposed in angle either side of probe 3a). Figure 7 is an experimental result that confirms this. The advantage of feeding two probes this way is that a significant increase in bandwidth can be obtained compared obtained with a single probe.

It can be seen that the patterns of Figures 4 to 7 have a significant backlobe, being substantially cosine (figure-of-eight) shaped in form. When transmitting in a given direction this implies a loss of power, when receiving this implies a loss of sensitivity and when direction finding there is a front-to-back ambiguity. The addition of a central internal or external monopole 4, as shown in Figures 3a and 3b, can be used to resolve the ambiguity or, by driving the monopole 4 and one or more of the dielectric resonator steering probes 3 simultaneously, the backlobe can be significantly reduced. This is shown experimentally by the measurements in Figure 8, where probes 3e and 3f and the monopole 4 are driven. It is possible to choose whether to cancel out or reduce either the backlobe or a corresponding front lobe by driving the monopole either in phase or in antiphase with the probes 3.

Referring now to Figures 9a and 9b, there is shown a slab of dielectric material 5, substantially hemispherical in cross-section, which is disposed on a grounded substrate 6 having a plurality of holes to allow access by cables and connectors to a

plurality of internal probes 7a to 7f. The probes 7a to 7f are disposed along radii at different internal angles.

In Figure 10, the circular lines represent power steps of 5 dB (decibels) and the arrows show the direction of the principal beam directions or "boresights". It can be seen that the pattern for probes A and C separately are disposed roughly 120 degrees in angle from each other and that the pattern for probes A and C excited simultaneously represents a new beam, formed electronically, with a boresight roughly half way between the two separate probe patterns.

Results for an example of the present invention are given here using a hemispherical dielectric resonator antenna fitted with internal probes. When probe 7a is driven (in either transmit or receive mode) and the remaining probes are open-circuited or otherwise terminated but not connected to the feed, then the measured azimuth radiation pattern labelled 'Probe A' in Figure 10 is obtained.

When probe 7c is connected instead of probe 7a, the measured azimuth radiation labelled 'Probe C' in Figure 10 is obtained. It can be seen that the beam has been steered incrementally by roughly the same angle as the probes are disposed internally (120 degrees in this case).

When probes 7a and 7c are driven simultaneously from a single source, using a power splitter/divider or similar power sharing device, and with the remaining probes open-circuited, the resulting measured azimuth radiation pattern is as radiation labelled 'Probe A&C' in Figure 10. It can be seen that the beam has been steered by roughly the angle bisecting the probes (60 degrees in this case). This method can be used to steer the beam continuously by continuously varying the feed power being shared between probes.

It can be seen that the patterns of Figure 10 have a significant backlobe, being substantially cosine (figure-of-eight) shaped in form. When transmitting, this implies a loss of power in the desired direction and the possibility of causing

interference in the opposite direction. When receiving, this implies a loss of sensitivity in the desired direction and the possibility of suffering interference from the opposite direction. When direction finding, there is a front-to-back ambiguity. The addition of a central internal or external monopole 8, as shown in Figures 11a and 11b, can be used to resolve this ambiguity or, by driving the monopole 8 and one or more of the dielectric resonator steering probes 7 simultaneously, the backlobe can be significantly reduced.

Figure 12a shows a cross-section through an embodiment of the present invention comprising a dielectric resonator 10 having a four-lobe cross-section, the cross-section being reminiscent of a four-leaf clover. The resonator 10 is disposed on a grounded substrate 12, and includes probes 13a, 13b, 13c and 13d, one in each lobe 11. The radiation patterns of this device are essentially cosine patterns of the type already shown in Figures 4 and 5.

This structure may be divided into segments and a single segment version is shown in Figure 12b, which depicts a grounded substrate 12 and one lobe 11 of the dielectric resonator 10 of Figure 12a, the lobe 11 being driven by a probe 13a. The lobe 11 is shown as bounded by generally vertical conducting walls 14, which are disposed at substantially 90° to each other. The advantage of such a single-probe quarter 'cloverleaf' antenna is that when the probe 13a is driven, the measured azimuth radiation of Figure 13 is obtained. The radiation frequency is 1378MHz at a bandwidth of 169MHz, and it can be seen that there is a significant reduction in backlobe in the direction from the probe 13a towards the centre of the dielectric resonator 10.

Figure 14 shows a solid spherical dielectric resonator 15 incorporating a dipole feed 16, thus obviating the need for a grounded substrate. This resonator 15 gives full beamforming coverage in all directions about the sphere.

Figure 15 shows a solid hemispherical dielectric resonator 16 disposed on a grounded substrate 17 and incorporating a monopole feed probe 18.

Figure 16 shows two solid hemispherical dielectric resonators 16 each provided with a monopole probe 18 and mounted back-to-back on either side of a shared grounded substrate 17. As with the embodiment of Figure 14, full beamforming coverage is provided in all directions.

Figure 17 shows two solid hemispherical dielectric resonators 16 each provided with a monopole probe 18 and each provided with a separate grounded substrate 17. The respective resonators 16 are then placed back-to-back such that the grounded substrates face each other but do not touch, the overall shape of the composite resonator being substantially spherical.

Finally, Figure 18 shows representations of the various shapes of dielectric resonator which are used in the present invention, including: right conical 20; non-right conical 21; truncated 22; non-truncated 23; stepped 24; non-stepped 25; non-circular cross-section 26; conical 27; pyramidal 28, 29; domed 30; spherical 31; part-spherical 32; amorphous 33; toroidal 34, 35; solid 36; cavity 37; hollow shell 38; oval cross-section 39; regular polygonal cross-section 40; irregular polygonal cross-section 41; lobed cross-section 42; and non-constant cross-section 43.

## CLAIMS:

1. A dielectric resonator antenna including a grounded substrate, a dielectric resonator disposed on the grounded substrate and a plurality of feeds for transferring energy into and from different regions of the dielectric resonator, the feeds being activatable individually or in combination so as to produce at least one incrementally or continuously steerable beam which may be steered through a predetermined angle, characterised in that the dielectric resonator has a cross-section that varies along an axis extending substantially perpendicularly from the grounded substrate.

2. An antenna as claimed in claim 1, further including electronic circuitry adapted to activate the feeds individually or in combination so as to produce at least one incrementally or continuously steerable beam which may be steered through a predetermined angle.

3. An antenna as claimed in claim 1 or 2, wherein the dielectric resonator has the form of a cone.

4. An antenna as claimed in claim 3, wherein the dielectric resonator has the form of a truncated cone.

5. An antenna as claimed in claim 3 or 4, wherein the dielectric resonator has the form of a right cone.

6. An antenna as claimed in claim 3 or 4, wherein the dielectric resonator has the form of a non-right cone.

7. An antenna as claimed in claim 1 or 2, wherein the dielectric resonator has the form of a pyramid.

8. An antenna as claimed in claim 7, wherein the dielectric resonator has the form of a truncated pyramid.

9. An antenna as claimed in claim 7 or 8, wherein the dielectric resonator has the form of a right pyramid.

10. An antenna as claimed in claim 7 or 8, wherein the dielectric resonator has the form of a non-right pyramid.

11. An antenna as claimed in claim 1 or 2, wherein the dielectric resonator has the form of a stepped cone.

12. An antenna as claimed in claim 11, wherein the dielectric resonator has the form of a truncated stepped cone.

13. An antenna as claimed in claim 11 or 12, wherein the dielectric resonator has the form of a stepped right cone.

14. An antenna as claimed in claim 11 or 12, wherein the dielectric resonator has the form of a stepped non-right cone.

15. An antenna as claimed in claim 1 or 2, wherein the dielectric resonator has the form of a stepped pyramid.

16. An antenna as claimed in claim 15, wherein the dielectric resonator has the form of a truncated stepped pyramid.

17. An antenna as claimed in claim 15 or 16, wherein the dielectric resonator has the form of a stepped right pyramid.

18. An antenna as claimed in claim 16 or 17, wherein the dielectric resonator has the form of a stepped non-right pyramid.

19. An antenna as claimed in claim 1 or 2, wherein the dielectric resonator has the form of a dome.

20. An antenna as claimed in claim 1 or 2, wherein the dielectric resonator has the form of a sphere.

21. An antenna as claimed in claim 1 or 2, wherein the dielectric resonator has the form of a portion of a sphere.

22. An antenna as claimed in claim 1 or 2, wherein the dielectric resonator has an amorphous form.

23. An antenna as claimed in claim 1 or 2, wherein the dielectric resonator has a substantially toroidal form.

24. An antenna as claimed in any preceding claim, wherein the dielectric resonator is substantially solid.

25. An antenna as claimed in any one of claims 1 to 23, wherein the dielectric resonator includes at least one cavity

26. An antenna as claimed in claim 25, wherein the dielectric resonator is a hollow shell.

27. A dielectric resonator antenna including a grounded substrate, a dielectric resonator disposed on the grounded substrate and a plurality of feeds for transferring energy into and from different regions of the dielectric resonator, the feeds being activatable individually or in combination so as to produce at least one incrementally or continuously steerable beam which may be steered through a predetermined angle, characterised in that the dielectric resonator has a non-circular cross-section.

28. An antenna as claimed in claim 27, further including electronic circuitry adapted to activate the feeds individually or in combination so as to produce at least one incrementally or continuously steerable beam which may be steered through a predetermined angle.

29. An antenna as claimed in claim 27 or 28, wherein the dielectric resonator has a substantially oval cross-section.

30. An antenna as claimed in claim 27 or 28, wherein the dielectric resonator has a regular polygonal cross-section.

31. An antenna as claimed in claim 27 or 28, wherein the dielectric resonator has an irregular polygonal cross-section.

32. An antenna as claimed in claim 27 or 28, wherein the dielectric resonator has a lobed cross-section.

33. An antenna as claimed in any one of claims 27 to 32, wherein the dielectric resonator has a cross-section which is substantially constant along an axis extending substantially perpendicularly from the grounded substrate.

34. An antenna as claimed in any one of claims 27 to 32, wherein the dielectric resonator has a cross-section which varies along an axis extending substantially perpendicularly from the grounded substrate.

35. An antenna as claimed in any one of claims 27 to 34, wherein the dielectric resonator is substantially solid.

36. An antenna as claimed in any one of claims 27 to 34, wherein the dielectric resonator includes at least one cavity

37. An antenna as claimed in claim 36, wherein the dielectric resonator is a hollow shell.

38. A dielectric resonator antenna including a dielectric resonator and at least one dipole feed for transferring energy into and from the dielectric resonator, the dipole feed having a longitudinal axis and being activatable so as to produce at least one incrementally or continuously steerable beam which may be steered through a predetermined angle, characterised in that the dielectric resonator has a cross-section that varies along an axis extending substantially parallel to the axis of the dipole feed.

39. A dielectric resonator antenna including a dielectric resonator and at least one dipole feed for transferring energy into and from different regions of the dielectric resonator, the dipole feed being activatable so as to produce at least one incrementally or continuously steerable beam which may be steered through a predetermined angle, characterised in that the dielectric resonator has a non-circular cross-section.

40. An antenna as claimed in any preceding claim, wherein the steerable beam may be steered through a complete 360 degree circle.

41. An antenna as claimed in any preceding claim, including electronic circuitry to combine the feeds to form sum and difference patterns to permit radio direction finding capability of up to 360 degrees.

42. An antenna as claimed in any preceding claim, including electronic circuitry to combine the feeds to form amplitude or phase comparison radio direction finding capability of up to 360 degrees.

43. An antenna as claimed in any preceding claim, wherein the feeds take the form of conductive probes which are contained within or against the dielectric resonator.

44. An antenna as claimed in any one of claims 1 to 37 and in any one of claims 40 to 43 depending from any one of claims 1 to 37, wherein the feeds take the form of apertures provided in the grounded substrate.

45. An antenna as claimed in claim 44, wherein the apertures are formed as discontinuities in the grounded substrate underneath the dielectric resonator.

46. An antenna as claimed in claim 45, wherein the apertures are generally rectangular in shape.

47. An antenna as claimed in any one of claims 44 to 46, wherein a microstrip transmission line is located beneath each aperture which is to be excited.

48. An antenna as claimed in claim 47, wherein the microstrip transmission line is printed on a side of the substrate remote from the dielectric resonator.

49. An antenna as claimed in claim 43, wherein a predetermined number of the probes within or against the dielectric resonator are not connected to the electronic circuitry.

50. An antenna as claimed in claim 49, wherein the probes are unterminated (open circuit).

51. An antenna as claimed in claim 49, wherein the probes are terminated by a load of any impedance, including a short circuit.

52. An antenna as claimed in any preceding claim, wherein the dielectric resonator is divided into segments by conducting walls provided therein.

53. An antenna as claimed in any preceding claim, wherein there is provided an internal or external monopole antenna which is combined with the dielectric

resonator antenna so as to cancel out backlobe fields or to resolve any front/back ambiguity which may occur with a dielectric resonator antenna having a cosine or 'figure of eight' radiation pattern.

54. An antenna as claimed in claim 53, wherein the monopole antenna is centrally disposed within the dielectric resonator.

55. An antenna as claimed in claim 53, wherein the monopole antenna is mounted above the dielectric resonator.

56. An antenna as claimed in claim 53, wherein the monopole antenna is mounted below the dielectric resonator.

57. An antenna as claimed in claim 53, wherein the monopole antenna is formed as an electrical combination of the feeds.

58. An antenna as claimed in claim 53, wherein the monopole antenna is formed as an algorithmic combination of the feeds.

59. An antenna as claimed in any preceding claim, wherein the dielectric resonator is formed of a dielectric material having a dielectric constant $k \geq 10$.

60. An antenna as claimed in any preceding claim, wherein the dielectric resonator is formed of a dielectric material having a dielectric constant $k \geq 50$.

61. An antenna as claimed in any preceding claim, wherein the dielectric resonator is formed of a dielectric material having a dielectric constant $k \geq 100$.

62. An antenna as claimed in any preceding claim, wherein a single transmitter or receiver is connected to a plurality of feeds.

63. An antenna as claimed in any one of claims 1 to 61, wherein a plurality of transmitters or receivers are individually connected to a corresponding plurality of feeds.

64. An antenna as claimed in any one of claims 1 to 61, wherein a single transmitter or receiver is connected to a plurality of non-adjacent feeds.

65. An antenna as claimed in any preceding claim, wherein the at least one feed is activatable so as to transfer energy into and from different regions of the dielectric resonator simultaneously at different frequencies so as to produce at least two beams of different frequencies in different predetermined directions.

66. A dielectric resonator antenna substantially as hereinbefore described with reference to Figures 9 to 18 of the accompanying drawings.

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| **Application No:** | GB 0017223.9 | **Examiner:** | Dr E.P. Plummer |
| **Claims searched:** | all | **Date of search:** | 16 October 2000 |

## Patents Act 1977
## Search Report under Section 17

**Databases searched:**

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.R): H1Q (QDX)

Int Cl (Ed.7): H01Q 9/04

Other: Online: INSPEC, PAJ, EPODOC, WPI, Internet

**Documents considered to be relevant:**

| Category | Identity of document and relevant passage | Relevant to claims |
|---|---|---|
| X | IEEE Transactions on Antennas and Propagation vol 46 no 3 March 1998 pp.425-433: GP Junker et al: Multiport Network Description and Radiation Characteristics of Coupled Dielectric Resonator Antennas - nb. final sentence of section I, figure 2, figure 7, paragraph linking pages 430 and 431. | 1,27,38,39 at least |
| Y | WPI abstract no. 1997-125147 & JP090008539A | 1,38 at least |
| Y | Electronics Letters 9.5.96 vol.32 no.10 pp.862-865: G Drossos et al: Switchable cylindrical dielectric resonant antenna | 1,38 at least |
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|---|---|---|---|
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